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# Estimation of Geometric Properties of Cortical Bone in Spinal Cord Injury

Eling D. de Bruin, MSc, Roland Herzog, PhD, Rients H. Rozendal, MD, PhD, Dieter Michel, MD, Edgar Stüssi, PhD

**ABSTRACT.** de Bruin ED, Herzog R, Rozendal RH, Michel D, Stüssi E. Estimation of geometric properties of cortical bone in spinal cord injury. *Arch Phys Med Rehabil* 2000;81:150-6.

**Objective:** To evaluate structural and geometrical properties of the tibia shaft in subjects with spinal cord injury (SCI) and subjects without SCI and to estimate the potential usefulness of a multimodal approach to diagnosing osteoporosis in SCI.

**Design:** A cross-sectional study of randomly selected SCI and non-SCI subjects.

**Methods:** Measurements of bone geometric indices by computed tomography, and calculated bending stiffness with a biomechanical testing method.

**Setting:** An SCI center hospital.

**Subjects:** Ten men without known orthopedic or neurologic impairments (controls), 10 men with SCI who had a history of lower extremity pathologic fracture since SCI, and 10 men with SCI who had never had lower extremity pathologic fracture.

**Results:** Analysis of geometric and structural indices of subjects' tibias found a significant difference in all geometric indices between controls and the SCI subjects with pathologic fracture history. Between the controls and the SCI subjects with no fracture history, however, differences were found only in cross-sectional area and calculated bending stiffness.

**Conclusion:** Structural analysis of leg bone, combined with measurement of bone density, may improve the ability to assess fracture risk in patients with SCI.

**Key Words:** Bone density; Osteoporosis; Rehabilitation; Spinal cord injury.

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**B**ONE MINERAL CONTENT and density measurements have been widely used in vivo to predict fracture risk.<sup>1-5</sup> The occurrence of fractures is not dependent on bone mass and density alone, however; bone structure and geometry also contribute to the integrity of the skeleton.<sup>6-12</sup> Myers and associates<sup>13</sup> found that the in vitro failure force of the distal radius was correlated with the distal radius width, cross-sectional area (CSA), and area moments of inertia (geometric indices of bone rigidity), but not with bone mineral content or density. Evidence from rat femora<sup>9</sup> also showed that the

strength and stiffness of the integrated diaphyses depended on both the second moment of area of the cross-section and body weight, but not on bone mineral density. Myburgh and colleagues<sup>14</sup> observed a substantial effect of bone width on bone stiffness. Recruits with low area moments of inertia of the tibia were found to have higher stress fracture morbidity than those with a high area moment of inertia in vivo.<sup>15</sup>

Estimation of bone strength requires knowledge of the material and geometric properties of bone. Bone strength is also dependent on environmental and individual factors, such as loading history. The relative contributions of each of these factors to overall bone strength is, for the most part, unknown.<sup>16</sup> New methods have therefore been developed that address not only bone mineral content and density but also the material and geometric properties of bone.<sup>17-27</sup> Such methods, however, have not been applied frequently to persons with spinal cord injury (SCI). Previous investigators studying the resistance of cortical bone to bending have not assessed the true area moments of inertia, ie, they did not consider how the bone mass is actually distributed along the CSA of the bone.

Nikolic and associates<sup>28</sup> observed small cortical area in several patients with paraplegia who had spontaneous fractures of the femur. Persons with long-term SCI show a significantly thinner cortical thickness, but no difference in polar moment of inertia, compared with individuals matched in age and size.<sup>29</sup>

One clinical effect of osteoporosis in paraplegia is pathologic fractures of lower-extremity long bones. These fractures occur in paraplegic patients with an incidence of 2% to 6%.<sup>30-32</sup> Long-bone fractures in SCI patients can be grouped into three classes<sup>33</sup>: (1) acute fracture suffered in the same accident that rendered the SCI (usually caused by high energy forces; their pathomechanics, configuration, and anatomic location do not differ from those seen in nonparalyzed patients); (2) pathologic fracture in an osteoporotic extremity (low energy injuries classically involving the proximal tibia or distal femur; they are defined as pathologic in this study); and (3) traumatic fracture in a chronic SCI patient who is involved in another violent accident (high energy input injuries that may occur in the normal osseous structure above the injury level or in the osteoporotic bones below the injury level).

In this study it is hypothesized that persons with long-term SCI who have experienced pathologic fractures have worse geometry and tibia quality than persons with long-term SCI who have not experienced fractures and control subjects without SCI. It is reasonable to believe that some individuals with SCI who have low bone mass also have cross-sectional geometry and bone quality poor enough to account for their fractures. Likewise, some individuals with SCI who have low bone mass may have favorable geometric properties that protect against fracture.

In the lower extremities of subjects with SCI, new steady-state levels for bone mineral content are reached at 2 years postinjury.<sup>34,35</sup> Therefore, in this study, long-term SCI is defined as SCI lasting for 2 or more years.

The mechanical properties of the tibia can be assessed by measuring the bending stiffness of the tibia using the phase velocity of flexural waves passing through it. In accordance

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with the Bernoulli-Euler model, the bending stiffness of a rotationally symmetrical long beam is proportional to the phase velocity of fourth-order flexural waves.<sup>36</sup> The validity of this relation for the tibia has been confirmed in vitro.<sup>36</sup> Bending stiffness for 21 tibias was measured using three-point bending tests and was compared with calculated bending stiffness from phase velocity and area moment of inertia of tibial bone, resulting in a very good correlation ( $r = .93$ ). To define the relation between bending stiffness and fracture resistance of tibial bone, all 21 tibias were loaded until fracture, giving an impression of maximum bending moment of the tibia bone. It was concluded that measurement of bending stiffness relates to fracture risk.<sup>36</sup> Results from an in vivo assessment of the bending stiffness of human tibias with a Bone Stiffness Measurement Device Swing (BSMD-Swing)<sup>a</sup> demonstrate that bone mineral measurements are not suitable predictors to evaluate changes in mechanical properties of long bones.<sup>37</sup>

The basic methodology employed in quantitative computed tomography (QCT) scanning involves the computation of the cross-sectional distribution of x-ray attenuation in a body by back-projecting the x-ray transmission measurements acquired at many angles around the body until the spatial arrangement of the absorbing structures can be determined.<sup>38</sup> With the information available from QCT scans, it is possible to isolate geometric changes and changes in density in both cortical and trabecular compartments.<sup>12</sup>

Interesting questions arise: (1) Does area moment of inertia and CSA of bone differ between individuals with long-term SCI who have experienced pathologic fracture since their SCI and those who have not experienced pathologic fracture, and between individuals with SCI and those without SCI (controls)? (2) In addition to measuring bone material (tissue) composition by Dual X-Ray Absorptiometry or QCT, would it also be useful to measure bending strength of bone as an organ? Hence, the aim of this study was to investigate, by means of CT and biomechanical testing, the mechanical and geometric properties of the tibia in men with SCI who have and have not experienced pathologic leg fractures since their SCI.

## MATERIALS AND METHODS

### Subjects

The subjects were selected from the population of men with SCI registered at the Swiss Paraplegic Center Nottwil, Switzerland, in 1997. At that time, the medical database revealed that 62 individuals had leg fractures after their SCI. After excluding subjects with fractures sustained concurrently with SCI, the names of 37 individuals remained. After we checked for study inclusion criteria (between the ages of 20 and 65 yrs, pathologic fracture, male, and more than 2 years since the SCI), 19 possible candidates remained. Information about the potential participants' fracture history before and after their SCI and the proximate causes of fractures were obtained by a telephone interview, administered about 2 weeks before the laboratory examinations. Lower-extremity fracture history was collected by a postal questionnaire and checked against X-ray records at the health center. The validity and reliability of the telephone interview were studied by analyzing the level of agreement between the self-reports and medical records of all the subjects who had sustained a leg fracture 2 or more years after SCI. One subject was excluded from further examination. A letter with information on the research was sent to 18 men with pathologic fracture history of the lower extremities after SCI. Of these 18 individuals, 3 were not able to make the journey to the hospital in the scheduled examination period, 3 could not be reached at their home address, 1 refused to participate, and 1 was ill during

the tests. The SCI fracture group thus was comprised of 10 individuals.

Ten men whose SCI occurred more than 2 years earlier and who had never had a lower extremity fracture, either before or since their SCI, and 10 men without known orthopedic or neurologic impairments were randomly selected from the hospital patient and employee population. The individuals in the three groups—subjects without known orthopedic or neurologic impairments (the Control group), individuals with SCI who had never had lower extremity fracture (the SCI group), and individuals with SCI and pathologic fracture history since their SCI (the SCI-Fx group)—were closely matched in age and size (table 1).

After they received written and oral information on the research, all subjects provided informed consent before the tests. Lesion level, Frankel classification according to the American Spinal Injury Association (ASIA)<sup>39</sup> protocol, and fracture site and history for the SCI-Fx group are reported in table 2. Lesion level, Frankel (ASIA) classification, and time since injury for the SCI group are reported in table 3. No subjects were receiving medication or treatment for osteoporosis.

### Computed Tomography

A Siemens SOMATOM Plus 4 CT scanner<sup>b</sup> was used to determine the CSA (defined as the total surface area of bone material in a plane perpendicular to the bone long axis) at six sections of the tibia. To assure geometrically similar sections along the leg, the leg length was defined as the distance from the medial condyle of the tibia to the ankle joint surface of the tibia. Three sections were measured within 5cm proximal to the middle of the tibia, and three within 5cm distal to the middle of the tibia. Sections were separated by 2cm. The sections represented the same region as the tibia section used for the bending stiffness measurements performed at the same hospital visit (fig 1). Examples of some of the measured sections are shown in figure 2.

The system parameters used in this study were as follows: a pixel size at x and y of 0.2mm, slice thickness of 2mm, pixel matrix of 512 × 512, and exposure factors of 120kV, 130mA, and 1.5sec/slice.

Data were analyzed on an alpha station with image processing software developed at the Laboratory for Biomechanics.<sup>a</sup> Three parameters were derived and calculated for a general characterization of the measured bone: (1) the CSA; (2) the area moment of inertia of the tibia with respect to the first main axis at diaphysis (IMAX) and (3) the area moment of inertia of the tibia with respect to the second main axis at diaphysis (IMIN). All parameters were calculated numerically from the CT scans. IMAX and IMIN reflect the properties of the tibia in the direction of greatest strength and smallest strength, respectively.

The CSA, IMAX, and IMIN of the following three section measurements were compared among the subject groups: the most proximal section (section A: CSA-A, IMAX-A, IMIN-A), the most distal section (section B: CSA-B, IMAX-B, IMIN-B),

Table 1: Subject Characteristics by Group

Group	Control	SCI	SCI-Fx	p
n	10	10	10	
Age (yrs)	35.3 ± 5.4	42.0 ± 11.7	42.0 ± 11.3	.2352
Body mass (kg)	75.4 ± 10.2	65.1 ± 9.1	68.6 ± 13.6	.128
Height (cm)	181 ± 7	175 ± 7	176 ± 6	.0823
Time since injury (yrs)	—	13.6 ± 9.6	20.1 ± 4.8	.07

Data reported as mean ± standard deviation.

Table 2: SCI-Fx Group: Injury and Fracture History

Subjects	Lesion Level/Frankel (ASIA) Classification	Time Between Fracture and SCI (yrs)	Bone Fractured	Cause of Fracture
1	T4/A	2	Left tibia, Left and right femur	Fell out of wheelchair
		14	Left femur	Ranging exercise of left knee joint
2	T4/A	8	Left tibia	Unknown to patient
		12	Right femur	Transfer from wheelchair to bed
3	T12/A	4	Right femur	Fell out of wheelchair
		10	Distal femur (left and right)	Slid forward out of wheelchair onto knees
4	C7-8/A	21	Distal femur/proximal tibia, left	Fell out of standing frame
		23	Left tibia	Fell out of wheelchair
		28	Left femur	Tried to change from lying to sitting while legs were crossed
5	C7/C	6	Right femur, distal	Fell out of wheelchair
		8	Right femur	Transfer from car to wheelchair
		20	Left femur	Fell out of wheelchair
6	T8/A	5	Right femur	Unknown, discovered during ranging exercises
7	T8/A	13	Right tibia, proximal	Transfer into car
		14	Left tibia, distal	Putting on a compression hose
8	L2/A	16	Right femur	Bending forward with the upper body while legs were crossed
9	T10-11/A	10	Right tibia	Fell out of wheelchair
10	L1/A	8	Right femur	Transfer from car to wheelchair
		14	Left femur	Fell out of wheelchair
		14	Left femur/right tibia	Fell out of wheelchair

and the mean value of all six sections (section C: CSA-C, IMAX-C, IMIN-C) (fig 1).

CT may show a 10.7% overestimation of CSA compared with the directly measured anatomic CSA. This may be because bone will be enlarged by the more radiolucent surrounding tissues in CT CSA, which might be related to how the back projection is filtered for generating images in CT technique.<sup>22</sup> This possible error was not corrected for in this study, under the assumption that this possible systematic difference would not affect our comparisons of the three involved groups.

### Bone Stiffness Measurement Device

Phase velocity propagation in the tibia was measured with the BSMD-Swing, which has been described in detail elsewhere.<sup>18,19,40,41</sup> For the measurements with the BSMD-Swing a standardized measurement protocol was followed. The right tibia of each subject was measured. Bending stiffness was calculated from the phase velocity values and anthropometric variables of the tibia in accordance with previously described procedures.<sup>36</sup> In this study the following formula (adapted from

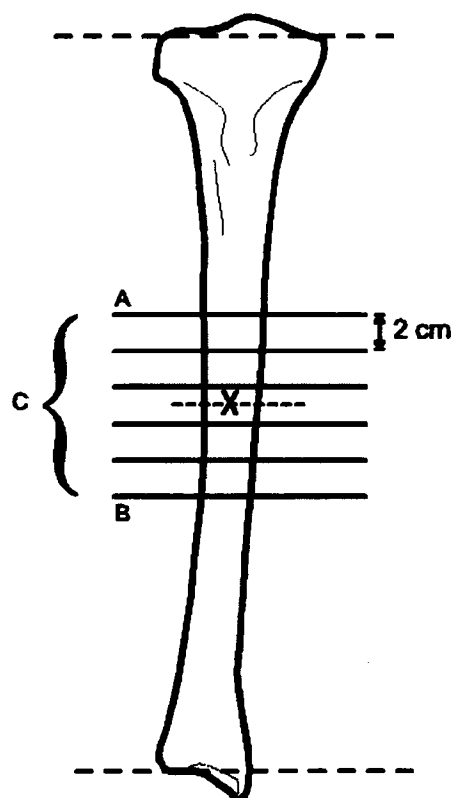


Fig 1. Anatomic locations of the tibial sections measured by CT scan. Section A represents the most proximal section, B the most distal section, and C the mean value of all measured variables for all six sections. The middle of the tibial shaft measured from the knee and ankle joint clefts is marked by "X." Individual sections are separated by 2cm.

Table 3: SCI Group: Injury History

Subject	Lesion Level/Frankel (ASIA) Classification	Time Since Injury (yrs)
1	C6-7/B	12
2	T12/A	15
3	L1-2/A	14
4	T12/A	3
5	C4/B	32
6	T5-6/A	6
7	T9/A	3
8	T10/A	26
9	T7/A	7.5
10	C6/A	17

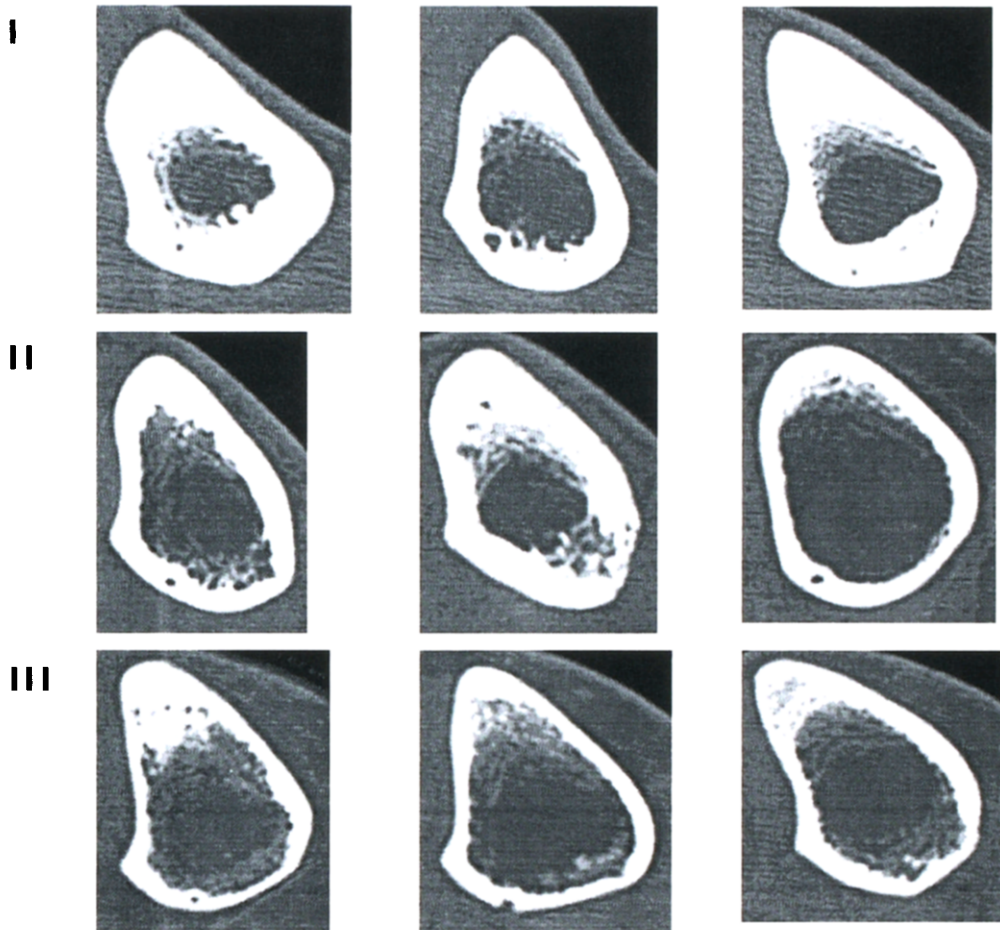


Fig 2. Three examples of cross sections through the shaft of the right leg tibia for (I) Controls, (II) SCI group, and (III) SCI-Fx group. The most proximal bone section (section A) is shown and all sectioned surfaces are viewed distally.

Bischof<sup>36</sup>) was used to calculate the bending stiffness:

$$B = 2.5 \times 10^{-7} \times (c^4 \times L \times b) + 100$$

where B = bending stiffness, c = measured flexural wave phase velocity, L = measured length of the tibia (length between lower border of the malleolus and medial knee joint cleft), and b = measured width of the facies medialis tibiae at the middle of the bone length.

#### Reproducibility of Bone Measurements

Reproducibility of routine patient measurements of the tibia with QCT has been determined to vary between .20% and .30%.<sup>42</sup> Measurements on actual test subjects with the BSMD-Swing have shown a receiver signal reproducibility within  $\pm 2\%$  (standard deviation).<sup>40</sup>

#### Statistical Analysis

Statistical analysis was performed with the SYSTAT statistical package.<sup>6</sup> For all tests, a significance level of  $p < .05$  was chosen unless otherwise indicated. To evaluate the statistical significance for mean differences between the three independent groups one-way analysis of variance (ANOVA) was used. Bonferroni post-hoc procedure was used for paired comparisons when the ANOVA yielded significant results (tables 1 and 4). A stepwise regression analysis was used to find the best factors to predict calculated bending stiffness. Analysis of

covariance (ANCOVA) and partial correlation coefficients were applied to control the effect of group on the best factors to predict calculated bending stiffness and on calculated bending stiffness.

## RESULTS

**Differences between groups.** No significant differences existed between the groups in mean age, body mass, and body height. The two SCI groups did not differ in mean duration since SCI (table 1).

**Differences in CSA.** CSA was significantly smaller in the SCI and SCI-Fx groups than in the Control group for all three section measurements (sections A and B, and the mean of all sections, C). There was no significant difference between the two SCI groups (table 4, fig 3).

**Differences in IMAX.** ANOVA showed a nonsignificant difference between groups in IMAX for section B ( $p = .0563$ ). This  $p$  value, however, approached the significant  $p$  level very closely; therefore, a Bonferroni post-hoc was performed on the data from this section as well. IMAX in the SCI-Fx group was significantly lower for section measurements A and C compared with the Control group, whereas the SCI group IMAX did not differ significantly from the Control group IMAX for any of the three section measurements. The IMAX of the SCI-Fx group for section B was not different from that of the Control group.

Table 4: ANOVA, by Group for IMAX, IMIN, CSA, Phase Velocity, and Calculated Bending Stiffness at the Right Leg for Sections A, B, and C

	Control	SCI	SCI-Fx	p
n	10	10	10	
IMAX-A (mm <sup>4</sup> )	$3.4 \times 10^4 \pm 1 \times 10^4$	$2.6 \times 10^4 \pm 0.2 \times 10^4$	$2 \times 10^4 \pm 0.9 \times 10^4$	.0064
IMAX-B (mm <sup>4</sup> )	$1.9 \times 10^4 \pm 0.6 \times 10^4$	$1.5 \times 10^4 \pm 0.3 \times 10^4$	$1.3 \times 10^4 \pm 0.6 \times 10^4$	.0563
IMAX-C (mm <sup>4</sup> )	$2.7 \times 10^4 \pm 0.7 \times 10^4$	$2 \times 10^4 \pm 0.5 \times 10^4$	$1.7 \times 10^4 \pm 0.7 \times 10^4$	.0052
IMIN-A (mm <sup>4</sup> )	$1.5 \times 10^4 \pm 0.5 \times 10^4$	$1.2 \times 10^4 \pm 0.2 \times 10^4$	$1 \times 10^4 \pm 0.3 \times 10^4$	.0278
IMIN-B (mm <sup>4</sup> )	$1 \times 10^4 \pm 0.4 \times 10^4$	$0.8 \times 10^4 \pm 0.1 \times 10^4$	$0.7 \times 10^4 \pm 0.2 \times 10^4$	.0527
IMIN-C (mm <sup>4</sup> )	$1.2 \times 10^4 \pm 0.4 \times 10^4$	$1 \times 10^4 \pm 0.1 \times 10^4$	$0.8 \times 10^4 \pm 0.3 \times 10^4$	.0175
CSA-A (mm <sup>2</sup> )	$341.8 \pm 61.1$	$245.8 \pm 42.2$	$200.6 \pm 45.8$	.0003
CSA-B (mm <sup>2</sup> )	$314.7 \pm 50.4$	$242.2 \pm 44.3$	$204.2 \pm 52.2$	.0003
CSA-C (mm <sup>2</sup> )	$340.6 \pm 52.2$	$257.7 \pm 46.3$	$209.8 \pm 52.8$	.0000
Phase velocity (ms <sup>-1</sup> )	$472 \pm 44$	$423.2 \pm 31.1$	$394.1 \pm 51.5$	.0015
Bending stiffness, right leg (Nm <sup>2</sup> )	$300.3 \pm 77.6$	$226.8 \pm 42.4$	$194.8 \pm 44.6$	.001

Data reported as mean  $\pm$  standard deviation.

No difference could be observed between the two SCI groups in IMAX for any of the three section measurements (table 4, fig 4).

**Differences in IMIN.** ANOVA showed a nonsignificant difference in IMIN for section B ( $p = .0527$ ). This  $p$  value, however, approached the significant  $p$  level very closely, so a Bonferroni post-hoc was performed on the data from this section as well. The IMIN of all three section measurements was significantly lower in the SCI-Fx group than in the Control group. There was no significant difference in IMIN between the SCI group and Control group for any of the three section measurements, and no significant difference in IMIN between the two SCI groups for any of the three section measurements (table 4, fig 5).

**Differences in calculated bending stiffness.** Calculated bending stiffness for both SCI groups differed significantly from that of the Control group, but no difference was found between the SCI and SCI-Fx groups (table 4, fig 6).

**Linear regression analysis.** Linear backward regression analysis suggested a direct relationship between IMIN-C and the length of the tibia and calculated bending stiffness ( $p < .005$ ,  $R^2 = 50.0\%$ ). Consequent ANOVA analysis revealed significant differences among the three groups for the IMIN-C parameter, indicating a significant correlation between IMIN-C and calculated bending stiffness. These results were similar after controlling the effect of group by ANCOVA.

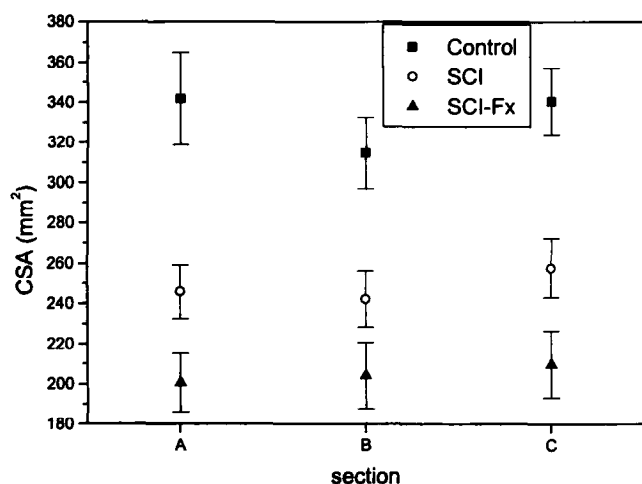


Fig 3. CSA: mean and standard error of the mean for the three tibial section measurements (A, most proximal; B, most distal; C, mean for all 6 sections) in each group (controls, SCI without fracture history, and SCI with fracture history).

## DISCUSSION

The midtibial shaft where the six measured CT sections were located consists mainly of cortical bone. When whole bones are subjected to experimental or physiologic loading conditions, their mechanical behavior is dependent not only on the mass of the tissue and its material properties but also on the geometry of the tissue. After SCI, bone mineral content in areas containing mainly compact bone diminishes at a rate of approximately 2% per month during the first year.<sup>43</sup> From animal experiments it is known that bone thinning in paralyzed limbs chiefly affects the bone shaft. The strength of such a paralyzed limb bone is greatly reduced, as shown by the large reduction of the bending moment needed to break the bone in both rats and kittens.<sup>44</sup> In the present study of men with SCI who had experienced pathologic fractures since SCI, men with SCI who had not experienced pathologic fractures since SCI, and men without known orthopedic or neurologic impairments, clear differences in geometric indices (CSA and area moments of inertia) were found between the subjects without known orthopedic or neurologic impairments and both groups of SCI subjects (ie, those with and those without pathologic fracture history). No significant difference in CSA was found between the two SCI groups. However, both groups showed a significantly smaller CSA than the control group for all three defined section measurements. The SCI groups appear to have a lower capacity to withstand loading on the bone. Load-carrying capacity in

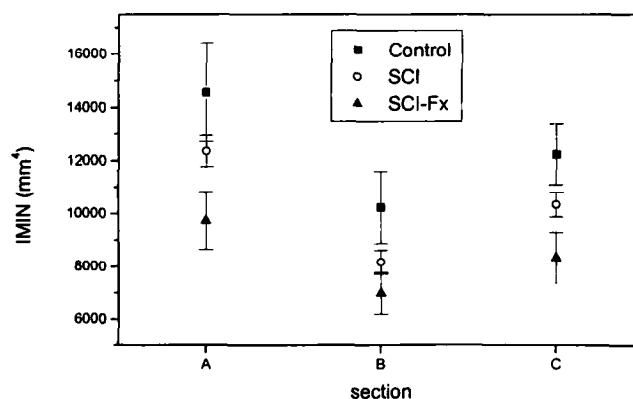


Fig 4. IMAX: mean and standard error of the mean for the three tibial section measurements (A, most proximal; B, most distal; C, mean for all 6 sections) in each group (control, SCI without fracture history, and SCI with fracture history).

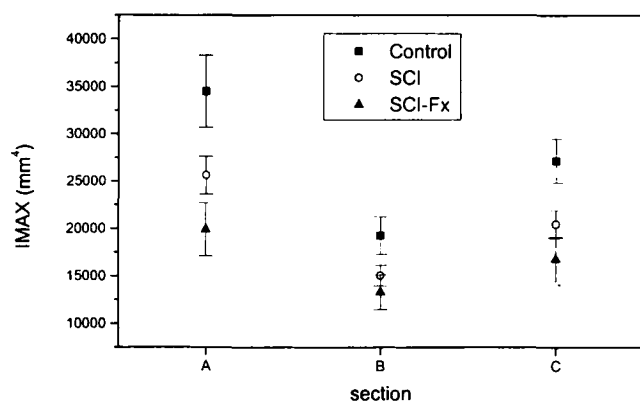


Fig 5. IMIN: mean and standard error of the mean for the three tibial section measurements (A, most proximal; B, most distal; C, mean for all 6 sections) in each group (1, controls; 2, SCI without fracture history; 3, SCI with fracture history).

bending is, however, dependent not only on the CSA of bone but also on how the bone mass is distributed within the CSA.

Bone strength is influenced by its geometric properties, such as the area moment of inertia, that indicate the distribution of bone mineral around the bone's bending axis.<sup>9,14</sup> The area moment of inertia is thus a measure of the bone's resistance to an imposed bending load. Our results showed the SCI-Fx group to have smaller moments of inertia at IMAX for sections A and C and at IMIN for sections A, B, and C, whereas the SCI group showed no differences in IMAX and IMIN for sections A, B, and C, compared with controls. IMAX and IMIN reflect the properties of the tibia in the direction of greatest and smallest strength, respectively. Our findings indicated different resistances to bending, in both the directions of the greatest and the smallest strengths of the tibia, in the two SCI groups. Subjects in the SCI-Fx group had lost more bone strength than those in the SCI group and thus were at higher risk for pathologic fracture.

Fracture occurrence also depends on loading conditions and loading history. Loading changes the configuration of deformable objects through the development of internal forces within the object.<sup>11</sup> For most people, daily activity and body weight are the principal sources of external loads on bone.<sup>45</sup> Although the

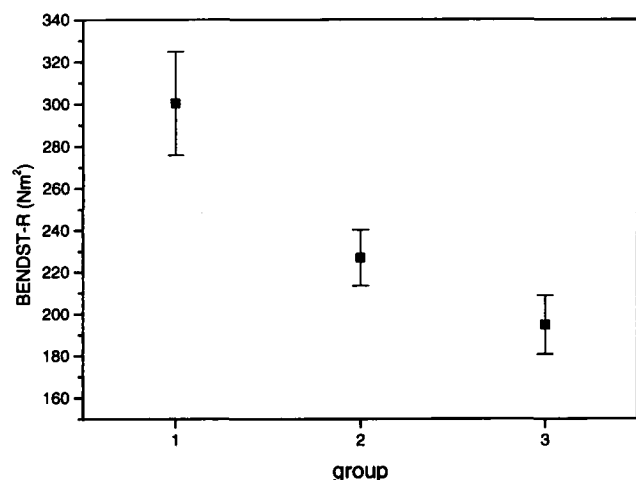


Fig 6. Calculated bending stiffness: mean and standard error of the mean for each group (1, controls; 2, SCI without fracture history; 3, SCI with fracture history).

specific loading conditions were unknown, the SCI groups, because of loss of lower extremity motor function, obviously have experienced less loading of the tibia during a substantial part of their lives. Absence of mechanical forces leads to a decrease in bone mass. Our results suggested that differences in geometric indices might reveal relevant information on bone strength properties. In a study similar to ours, 78-year-old women with high and low calcaneal bone mineral density showed no group differences in the area moments of inertia.<sup>22</sup> It has also been observed that the increased bone porosity in old age is compensated by an increased area moment of inertia.<sup>6</sup> The redistribution of bone mass can compensate for loss in bone material strength, and thus the supportive function and resistance to bending of bone are better maintained.<sup>14</sup> In the present study only the SCI-Fx group had a substantial decline in the cross-sectional moment of inertia (area moment of inertia), which indicates the distribution of bone mineral around the bone's bending axis. This decline might be from a combination of bone loss and less optimal compensatory geometric structuring following the SCI. Since ours was a cross-sectional study we could not evaluate the restructuring of the geometric features after SCI. However, a longitudinal study on changes of tibia bone in short-term SCI revealed a rapid and immediate change in area moments of inertia in 2 of 10 subjects.<sup>46</sup> Further research into the area moments of inertia of tibia bone is needed to substantiate the speculated importance of this factor and its contribution to whole bone strength.

Although osteoporosis results from a complex, incompletely understood set of physiologic and biochemical conditions, the symptom is purely mechanical: a bone fractures without tolerating the desired load. The quality of a bone—its ability to resist such mechanical failure—is a biomechanical property. The bone's ability to resist forces like tension, compression, torsion, and bending is dependent, among other factors, on its geometry. The bending strength of a bone is a function of the area moment of inertia about the axis of bending for the particular cross-section of bone studied. In this study a linear backward regression analysis suggested a direct relationship between IMIN-C (the mean of values for the middle part of the tibial shaft) and the length of the tibia and its calculated bending stiffness, leading us to the conclusion that the BSMD-Swing has the potential to deliver clinically relevant information on the mechanical properties of tibia bone in patients with SCI.

## CONCLUSIONS

Our study confirmed the hypothesis that men with long-term SCI who have experienced pathologic fractures have worse geometry and quality of the tibia bone than men with long-term SCI who have not had fractures and control subjects without SCI. It seems reasonable to believe that in some individuals with SCI, poor geometry and quality may account for their fractures. Area moment of inertia, CSA, and bending stiffness of long lower extremity bone, combined with bone mineral density measurements, are likely to discriminate better than density measurements alone the bone strength and fracture risk in persons with SCI. Combined measurements of these factors could, in the long term, improve fracture risk prediction in patients with SCI.

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#### Suppliers

- a. Laboratory for Biomechanics ETHZ, Wagistrasse 4, CH-8952 Schlieren, Switzerland.
- b. Siemens AG, Post Box 3240, Werner von Siemensstrasse 50, D-91052 Erlangen, Germany.
- c. SPSS Inc., 444 North Michigan Avenue, Chicago, IL 60611.